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Zone-subsoiling effects on infiltration, runoff, erosion, and yields of furrow-irrigated potatoes

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ABSTRACT

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Soil compaction is a problem in many Pacific Northwest fields. We hypothesized that zone subsoiling would improve potato (*Solanum tuberosum* L., cv. 'Russet Burbank') yield or grade, increase infiltration, and decrease bulk density, runoff, and erosion of furrow-irrigated fields, while maintaining trafficability and irrigability of furrows. A 2 year study was established on a Portneuf silt loam (coarse-silty, mixed, mesic Durixerollic Calciorthids). In the fall, plots were in wheat stubble (1988) or bean stover (1989), and were either disked (10–12 cm), chiselled (25–30 cm), or moldboard plowed (20–25 cm). Fall tillages were split in spring, half of each plot receiving in-row zone subsoiling (46 cm) after planting potatoes. The effect of zone subsoiling on infiltration in 1989 was small because of variation across fall tillages. In 1990, zone subsoiling increased infiltration by 10% across fall tillages. Erosion decreased up to 278% with zone subsoiling. Zone subsoiling reduced erosion more effectively than it increased infiltration, shown by a two- to three-fold decrease in the sediment loss to water infiltrated ratio. Zone subsoiling increased infiltration and reduced erosion more in 1990 when the study was conducted on a slightly steeper slope with higher water application rates than in 1989. In 1989, zone subsoiling increased the yield of grade 1 tubers by 3.8 t ha^{-1} (4.6%), but the total yield was not significantly increased. In 1990, zone subsoiling increased the total yield by 4.2 t ha^{-1}, and the yield of grade 1 tubers by 5.6 t ha^{-1} (7.7%). With zone subsoiling, the percentage of large grade 1 market-grade tubers increased by 3.3% in 1989 and 5.7% in 1990. Zone subsoiling requires some extra attention by the irrigator early in the season to insure uniform furrow irrigation, but it can potentially conserve both soil and water while improving grade and yield.

INTRODUCTION

About 1.5 million ha of agricultural land are surface irrigated in Washington, Oregon, and Idaho. In 1988, 205 000 ha were in potato production. In recent years there has been a substantial shift away from furrow to sprinkler irrigation of potatoes, the two major factors driving this shift being soil erosion, and tuber market grade and processing quality.

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Erosion is a severe threat to sustainability of Pacific Northwest agriculture. The soils of this region are derived from ash and loess, are low in organic matter and clay, and are weakly structured with few durable aggregates. From 5 to 50 t of soil ha^{-1} $year^{-1}$ can be lost from typical fields, and up to three times that amount from near the furrow inlets (Berg and Carter, 1980; Kemper et al., 1985). Mech (1959) reported 50.9 t ha^{-1} soil loss from a single 24 h irrigation. As many arid soils have subsoils rich in calcium carbonate, their exposure, or mixing with surface soil can cause severe plant nutrient deficiencies and soil physical problems. These eroded portions of fields reduce crop productivity and increase the inputs required to sustain yields (Carter et al., 1985). Approximately 70% of the furrow-irrigated fields in the study area are affected by this problem.

Recent studies from Kimberly, implicated inadequate wetting of the hill in furrow-irrigated fields of 'Russet Burbank' potatoes as a problem affecting tuber quality (T.J. Trout, personal communications, 1991). These plants are water-stressed during hot weather, and tubers become exposed to dry soil and high soil temperature in the hills, especially before complete canopy coverage. Compaction on these soils exacerbates the problem by reducing rooting in the soil zones with available soil water, and by forcing tuber set higher in the hill where temperatures and soil water availability are less favorable. Compaction may also constrain tubers as they increase in volume.

Furrow erosion can be reduced by various approaches, including minibasins and buried pipes to control runoff (Carter, 1985), straw in furrows (Berg, 1984; Brown, 1985), and furrow sodding (Cary, 1986). These alternatives are costly or management intensive. Sediment in minibasins must also be spread on fields periodically to effectively combat erosion. Conservation tillage systems for furrow-irrigated agriculture exist but are not widely accepted (Carter and Berg, 1991).

Long-term compaction management requires a reduction of traffic, the restriction of traffic to limited traffic lanes, and use of rotations and cultural practices (such as residue incorporation) that promote stable soil aggregation. In the short term, some form of deep loosening is required (Glinski and Lipiec, 1990). Zone subsoiling (sometimes called precision subsoiling or in-row subsoiling) is more energy efficient and cost effective than total loosening, and has the additional advantage of maintaining firm traffic lanes for field re-entry. Zone subsoiling with the Tye Paratill[1] loosens a zone under the row but the implement shank is laterally displaced from the row. This prevents the creation of deep loose troughs directly under planted seeds and allows the zone subsoil operation to be conducted after planting.

[1]Mention of trademarks, proprietary products, or vendors does not constitute a guarantee or warranty of the product by the USDA, and does not imply its approval to the exclusion of other products or vendors that may also be suitable.

Deep loosening for irrigated potatoes improves yield and grade, particularly for the 'Russet Burbank' variety (Bishop and Grimes, 1978; Campbell and Moreau, 1979; Ross, 1986; Miller and Martin, 1987, 1990; Ibrahim and Miller, 1989; Parker et al., 1989). Most studies used sprinkler irrigation because water delivery down a furrow with surface irrigation would be a serious problem after total loosening by deep tillage. It was not clear whether this would occur for zone subsoiling confined to zones directly under the hill, leaving furrow areas undisturbed. Erosion can be reduced by increasing infiltration, which raises irrigation efficiency and reduces runoff. Deep tillage increases infiltration by increasing porosity. The objectives of this study were to determine the influence of zone subsoiling on soil bulk density in the potato hill, infiltration, runoff, and erosion from furrow-irrigated 'Russet Burbank' potatoes, and to evaluate zone subsoiling effects on tuber yield and grade.

METHODS AND MATERIALS

A 2 year field study was established near Kimberly, with different fields used each year to avoid disease problems. Potatoes (*Solanum tuberosum* L. c.v. 'Russet Burbank') were preceded by winter wheat (*Triticum aestivum* L. c.v. 'Fieldman') the first year of the study and by beans (*Phaseolus vulgaris* L. c.v. 'Viva Pink') the second year. Both fields were classified as Portneuf silt loam (coarse-silty, mixed, mesic Durixerollic Calciorthids). The two fields were within 0.5 km of one another. The field slopes were 0.68% and 0.91% in the first and second years, respectively. All data presented are from observations made during the 1989 and 1990 growing seasons and will be referred to as such.

Tillage main plots, established in the fall of 1988 and 1989, were: disked (10–12 cm), chiselled (25–30 cm), or moldboard plowed (20–25 cm). These were split for the zone subsoiling into subplots which were subsequently split for two N placement treatments. The 1989 statistical design was a split-plot, split-block in four replicates, with randomized fall tillage main plots that were split randomly for zone subsoiling after planting or undisturbed after planting. Zone subsoiling split plots were non-randomly split for band vs. broadcast N application. The 1990 statistical design was a randomized split-split plot in three replicates, with fall tillage main plots randomly split for zone subsoiling after planting and for broadcast vs. band application of nitrogen. Fertilizer placement responses will be addressed in a subsequent paper.

The fields were soil sampled each spring and fertilizers applied according to University of Idaho soil test recommendations (McDole et al., 1987). In early April 1989 and 1990, 60 and 100 kg ha^{-1}, respectively, of P containing 3.9 kg a.i. ha^{-1} Eptam (EPTC) was broadcast over the entire study area. A broadcast application of 224 kg N ha^{-1} was applied on the appropriate split-plot area. Each study area was then disked (10–12 cm) and roller harrowed (2–4 cm) to incorporate chemicals and fertilizer.

Potatoes were planted on 27 April 1989 and 2 May 1990 with a custom-built, two-row semi-automated planter/hiller. Nitrogen, at the same rate and formulation as used on the broadcast plots, was banded on the other half of the split plot at the same depth and 10 cm to the side of the seed piece during the planting operation. In 1989, Temik (Aldicarb) at 3.4 kg a.i. ha^{-1} was placed with the seed. In 1990, Thimet (Phorate) at 2.8 kg a.i. ha^{-1} was placed with the seed and Dyfonate (Forofos) at 4.5 kg a.i. ha^{-1} was lightly incorporated in the hill during planting.

Following planting, zone subsoiling was carried out on the appropriate plot on 2 May 1989, and 4 May 1990 with a Tye Paratill. The Paratill (marketed as a "potato special") had four Paratill shanks mounted on a 4.6 m welded frame consisting of a triple 10.2 cm × 10.2 cm tool bar for mounting of Paratill shanks and subsidiary tillage tools. Paratill shanks were mounted 15.2 cm and 167.6 cm from the centerline on each side of the tractor, with the innermost shank angled outward and the outermost shank angled inward. The two center shanks were staggered longitudinally on the frame to prevent interaction of the two closely-spaced shanks. The maximum tillage depth was approximately 46 cm. This arrangement provided a 30.5 cm zone of undisturbed soil in non-traffic furrows and a slightly wider, but less definite zone of undisturbed soil in traffic furrows. In the same pass, using weighted furrow-forming tools on the rear tool bar, these undisturbed areas were formed into 60° V-shaped furrows approximately 20 cm deep.

All plots were eight rows wide with an interrow spacing of 91.5 cm. Potatoes were planted at 30 cm intrarow spacing of 36 500 seed pieces ha^{-1}. In both years, the final stand was 100% of the planted stand. Tillage subplots were 67 m long in 1989 and 107 m long in 1990. The exact furrow lengths for each tillage subplot were determined and used to calculate water application, runoff, infiltration, and erosion rates.

Water application was by gravity-fed furrow irrigation. Each monitored furrow was adjusted to a single application rate. With minor exceptions a given application rate was held constant throughout each irrigation event. Depending on field conditions, application rates varied slightly among irrigation events to achieve adequate furrow advance in all treatments. Application rates were 10–20% higher for the first two irrigations in each season, and for irrigations after the onset of vine senescence in late August. Both median and modal application rates for 1989 were 13.3 l min^{-1} and for 1990 were 15.1 l min^{-1} per irrigated furrow. During each irrigation event every other furrow was irrigated, alternating between traffic (rear wheel-track) furrows and non-traffic furrows with each successive irrigation event. The duration of each pair of irrigations (traffic and non-traffic) varied through the season to meet the crop water demand. Irrigations were twice weekly (one in traffic furrows, one in non-traffic furrows) except very early and very late in the season when irrigation intervals were extended. The amount of runoff was determined from runoff flow rate and duration, using calibrated V-notch flumes that were visually read at 1–2 h intervals (or shorter) during the course of the irrigation set. The 60° V-notch flumes, originally developed and calibrated by Robinson and Chamberlain (1960) are marketed by Honkers Supreme, Twin Falls, ID, and satisfy the hydraulic requirements for long-throated flumes (Bos et al., 1984) up to a flow depth of 9 cm (a gauge reading of 10 cm, or 100 l min^{-1} flow rate). Furrow infiltration was determined from the difference of inflow and runoff volumes.

Sediment samples (1 l) were collected from the free-flowing flume discharge at each reading. The weight of sediment per liter of runoff was determined from the settled volume of sediment in Imhoff cones (Sojka et al., 1992). This technique calibrated the volume of settled sediment and the weight of sediment per unit volume of runoff (R^2=0.99 for more than 0.5 g l^{-1}). Sediment monitoring was discontinued in 1989 when the sediment content of runoff samples was below 0.5 g l^{-1}.

Soil temperatures were determined in both years at depths of 5, 15, and 25 cm in the hill by thermocouple and logged four times hourly. Hill soil bulk density was determined at two locations per plot in the disked, plowed, and plowed+zone-subsoiled treatments to 0.45 m in 0.15 m increments in June and August of 1989, and in August 1990 using the gamma ray backscatter technique (Freitag, 1971). Locations were averaged for the plot observation. Correction for soil water content to obtain dry bulk density was accomplished by neutron attenuation soil water determination at the same soil depths.

In 1990 five shoots were harvested from each subplot 8–10 days after emergence on 5 June to compare shoot dry weight among treatments. Mid-season samples from 1.5 m of row were dug by hand on 19 July and 24 August 1989 and on 18 July and 27 August 1990, to characterize shoot dry weight, tubers, and easily recoverable roots, and tuber fresh weight to characterize bulking and nutrient uptake. Final tuber yield and quality were determined in early October on machine-harvested samples, taken from the center 15.2 m of two rows in each plot. Potato market grade was determined using USDA grading standards (Anonymous, 1983) and specific gravity was determined using the weight in air minus weight in water method (Kleinschmidt et al., 1984).

RESULTS AND DISCUSSION

Soil bulk density

The effect of zone subsoiling on hill bulk density was assessed in three of the six tillage treatments at mid-season, twice in 1989 and once in 1990 (Ta-

TABLE 1

Bulk densities (g cm^{-3}) determined in the center of hills of three tillage treatments, using a gamma ray backscatter technique

	28 June 1989			16 August 1989			2 August 1990		
Depth (cm)	Disk only	Plow only	Plow +ZS[1]	Disk only	Plow only	Plow +ZS	Disk only	Plow only	Plow +ZS*
15	1.27[a]	1.25[a]	1.15[a]	1.26[a]	1.25[a]	1.23[a]	1.15[a]	1.11[a]	1.05[a]
30	1.35[a]	1.36[a]	1.24[b]	1.33[a]	1.38[a]	1.24[b]	1.41[a]	1.36[a]	1.16[b]
45	1.35[a]	1.38[a]	1.37[a]	1.36[a]	1.44[a]	1.37[a]	1.52[a]	1.45[a]	1.37[b]

[1] +ZS, with zone subsoiling.
*Values in the same row for the same date with the same superscript do not differ at the 5% probability level, using the Duncan's multiple range procedure.

ble 1). A common potato tillage regime under furrow irrigation corresponds to the fall-plowed without spring zone subsoiling treatment. Fall disking without spring subsoiling is the most compaction-prone tillage practice likely to be encountered in commercial production, and fall plowing plus spring zone subsoiling provides the greatest compaction disruption feasible for commercial production. Bulk densities were generally unaffected by zone subsoiling 15 cm from the top of the hills, but were reduced at the 30 cm depth in both years. In 1990, reduced bulk density with zone subsoiling was also observed on 2 August at 45 cm. The difference at 45 cm appears to be caused by higher initial bulk densities in 1990 than in 1989. The first bulk densities were obtained more than 1 month after the subsoiling operation. There were several intervening irrigations which may have induced some consolidation; however, lower bulk densities in the subsoiled treatment were still apparent. These differences remained until late into the season.

Infiltration

A summary of the statistical significance of seasonal totals for treatment-related infiltration and sediment loss is presented in Table 2. In 1989, zone subsoiling increased infiltration in the chisel treatments for both traffic and non-traffic furrows (Table 3). Also, chiseling can reduce infiltration, disturbing macropore flow (Meek et al., 1992). Zone subsoiling significantly decreased infiltration in the plow, non-traffic furrows, while having no appreciable effects in the disk treatments. The effects of these interactions, zone subsoiling with fall tillage and wheel traffic furrows, became larger as the season progressed (Figs. 1 (a) and 1 (b)). Infiltration differences between traffic and non-traffic furrows also continued to become larger in all fall tillage treatments (slopes of infiltration curves differed on all dates).

In 1990 the infiltration was consistently higher in non-traffic furrows re-

TABLE 2

Probability levels ($P_r > F$) for seasonal cumulative infiltration and seasonal cumulative sediment loss for 1989 and 1990 for major sources of variance (infiltration and sediment loss data appear in Table 3)

	1989		1990	
Source of variance	Infiltration	Sediment	Infiltration	Sediment
Fall tillage (FT)	0.0016	0.3381	0.5386	0.1293
Zone subsoiling (ZS)	0.7704	0.4096	0.0001	0.0010
FT×ZS	0.0538	0.0950	0.9112	0.4049
Wheel traffic (WT)	0.0001	0.0001	0.0001	0.0009
FT×WT	0.0232	0.7776	0.9322	0.5975
ZS×WT	0.0073	0.2806	0.0001	0.0007
FT×ZS×WT	0.0007	0.1094	0.4784	0.4067

gardless of fall tillage (Table 3, Figs. 2(a) and 2(b)). Similarly, infiltration was greater for zone-subsoiled plots regardless of fall tillage and irrespective of traffic or non-traffic furrow. In 1990 the increased infiltration of the zone-subsoiled treatment for non-traffic furrows was caused almost entirely by differences in the first irrigation. Slope changes for subsoiled vs. non-subsoiled accumulation curves of non-traffic furrows were nearly identical, and were merely offset by the difference that occurred on the first irrigation (Figs. 2(a) and 2(b)). Infiltration differences in traffic furrows, with or without zone subsoiling, continued throughout the season, as is evident from the steadily changing slope difference between pairs of accumulation curves in all three fall tillage treatments.

The soil moisture differences at the time of planting and the subsoiling–planting operations probably explain the substantial infiltration response reversal of the fall-plowed treatment with or without subsoiling between the 2 years. The wheel traffic patterns of zone-subsoiled plots and non-subsoiled plots were different, because planting was with two-row equipment and zone subsoiling was with four-row equipment. Non-subsoiled plots had a true non-traffic furrow, whereas zone-subsoiled plots did not.

The surface 30 cm of soil was relatively dry in the spring of 1989 at the time of both planting and subsoiling. In contrast, planting and subsequent subsoiling was delayed in 1990 because of untimely rain. Even though 1990 spring field operations before planting were minimal, they caused more surface compaction than in 1989. These operations reduced the infiltration differences between the true non-traffic furrows vs. the traffic furrows in 1990. The contrast in accumulation curve patterns for the 2 years is quite pronounced for the fall plow treatment (Fig. 1(a) vs. 2(b)), which was the loosest of the fall tillage treatments and therefore most susceptible to recompaction in 1990. The true non-traffic furrow of the fall plow treatment in 1989 (without sub-

TABLE 3

Season summary of water infiltration cumulative sediment loss for 1989 and 1990

Treatment	Traffic furrows			Non-traffic furrows			All furrows		
	Sediment loss (kg ha^{-1})	Infiltration (mm)	Sed.: infiltr.[1] (kg mm^{-1} ha^{-1})	Sediment loss (kg ha^{-1})	Infiltration (mm)	Sed.: infiltr. (kg mm^{-1} ha^{-1})	Sediment loss (kg ha^{-1})	Infiltration (mm)	Sed.: infiltr. (kg mm^{-1} ha^{-1})
1989									
Disk −ZS[2]	645	280	8.6	227	411	1.75	872	691	4.25
Chisel −ZS	1530	249	21.8	621	361	5.76	2151	610	11.95
Plow −ZS	1288	315	15.1	96	545	0.57	1384	861	5.45
Disk +ZS	1313	257	17.8	405	410	3.12	1718	668	8.42
Chisel +ZS	676	329	6.9	233	435	1.78	909	764	3.95
Plow +ZS	626	330	6.0	253	433	1.92	879	763	3.72
Mean disk	979	269	13.1	316	411	2.44	1295	679	6.35
Mean chisel	1103	289	13.1	427	398	3.55	1530	687	7.50
Mean plow	957	323	10.1	175	489	1.16	1132	812	4.62
Mean −ZS	1154	281	15.0	315	439	2.31	1469	721	6.90
Mean +ZS	871	306	9.5	297	426	2.27	1168	732	5.24
1990									
Disk −ZS	6815	252	33.6	935	368	3.17	7756	620	15.57
Chisel −ZS	10515	250	52.1	1141	376	3.77	11540	626	36.85
Plow −ZS	8003	259	38.4	851	387	2.71	8988	647	16.83
Disk +ZS	2578	314	10.4	750	393	2.34	3297	708	5.86
Chisel +ZS	2900	320	11.5	748	396	2.31	3674	717	6.32
Plow +ZS	2334	327	9.0	816	404	2.47	3192	731	5.34
Mean disk	4697	283	20.9	842	381	2.74	5527	664	10.39
Mean chisel	6708	285	29.5	945	386	3.01	7607	671	14.15
Mean plow	5168	293	22.1	834	396	2.58	6090	689	10.78
Mean −ZS	8450	254	41.2	976	377	3.21	9428	631	18.52
Mean +ZS	2604	321	10.3	771	398	2.37	3388	718	5.84

[1]Infiltration is only during sediment monitoring.
[2]Use or no use of zone subsoiling is indicated by +ZS or −ZS, respectively.

soiling) received little compaction before irrigation. Another contributing factor is probably the slightly steeper slope in 1990 compared with 1989.

A practical consideration was the tendency of furrow streams to flow into the soil discontinuity formed by the zone-subsoiling shank. This "piping" of water occurred despite the fact that Paratill shanks were offset from the furrow and did not actually disturb soil in the furrow. Piping continued at a given point in the furrow until that hill area became saturated or until the hill slumped, rediverting water down the furrow. Piping was a greater problem in the non-traffic furrows of zone-subsoiled treatments. Presumably the more diffuse fracture area and wheel compaction from the deep tillage operation promoted better furrow shaping and water conveyance. Piping was most pronounced in the first few irrigations of each season, after which it was not as serious. A brief surge irrigation to condition the furrows before the beginning of regular irrigations in 1990 reduced, but did not eliminate this problem. Attention to initial furrow shaping and problems in the first few irrigations will significantly reduce the impact of this problem.

Runoff and erosion

The magnitude of erosion increased three- to sixfold from 1989 to 1990, despite smaller amounts of water applied (590 mm vs. 450 mm, respectively) and water infiltrated (Table 3). This was caused by differences in field slope (0.68% in 1989 and 0.91% in 1990) and median furrow inlet rates (13.25 l min^{-1} in 1989 and 15.14 l min^{-1} in 1990). In addition, the crop preceding the 1989 study was wheat, which left more residue than the bean crop which preceded the 1990 study. Sediment sampling ended for the 1989 season in mid-June (Figs. 1(a) and 1(b)) when most sediment concentrations were below 0.5 g l^{-1} in nearly all plots.

The shallower slope and lower furrow inlet rate in 1989 minimized the magnitude of treatment runoff and erosion differences (Table 3, Figs. 1(a) and 1(b)). Among non-subsoiled treatments, fall chiseling lost twice the amount of soil as the other treatments either as mass of sediment per unit area or per unit volume of water infiltrated. Among zone-subsoiled treatments, fall disking lost more sediment than the other treatments regardless of wheel traffic. Erosion from non-traffic furrows was always less than that from traffic furrows. Few additional inferences can be made from the 1989 data because erosion was below the measurement threshold early in the season for most treatments, and the magnitude of treatment differences were relatively small.

In 1990 erosion was clearly driven by runoff differences among treatments (Figs. 2(a) and 2(b)). Where infiltration was improved, furrow sediment loss was reduced. Traffic furrows lost more sediment than non-traffic furrows. Erosion from non-traffic furrows was unaffected by fall tillage, producing low amounts of sediment in all cases. In traffic furrows, erosion was three-

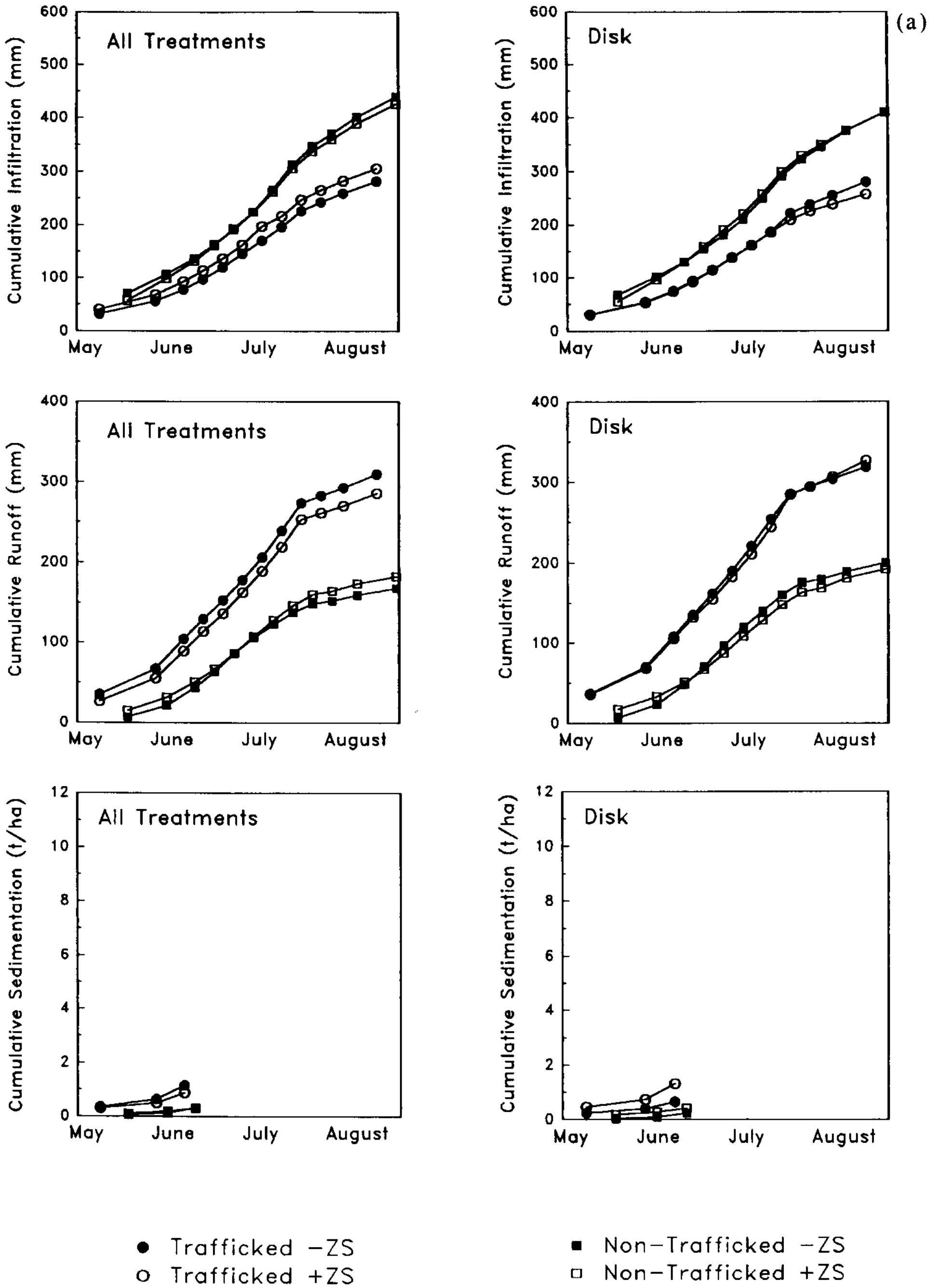
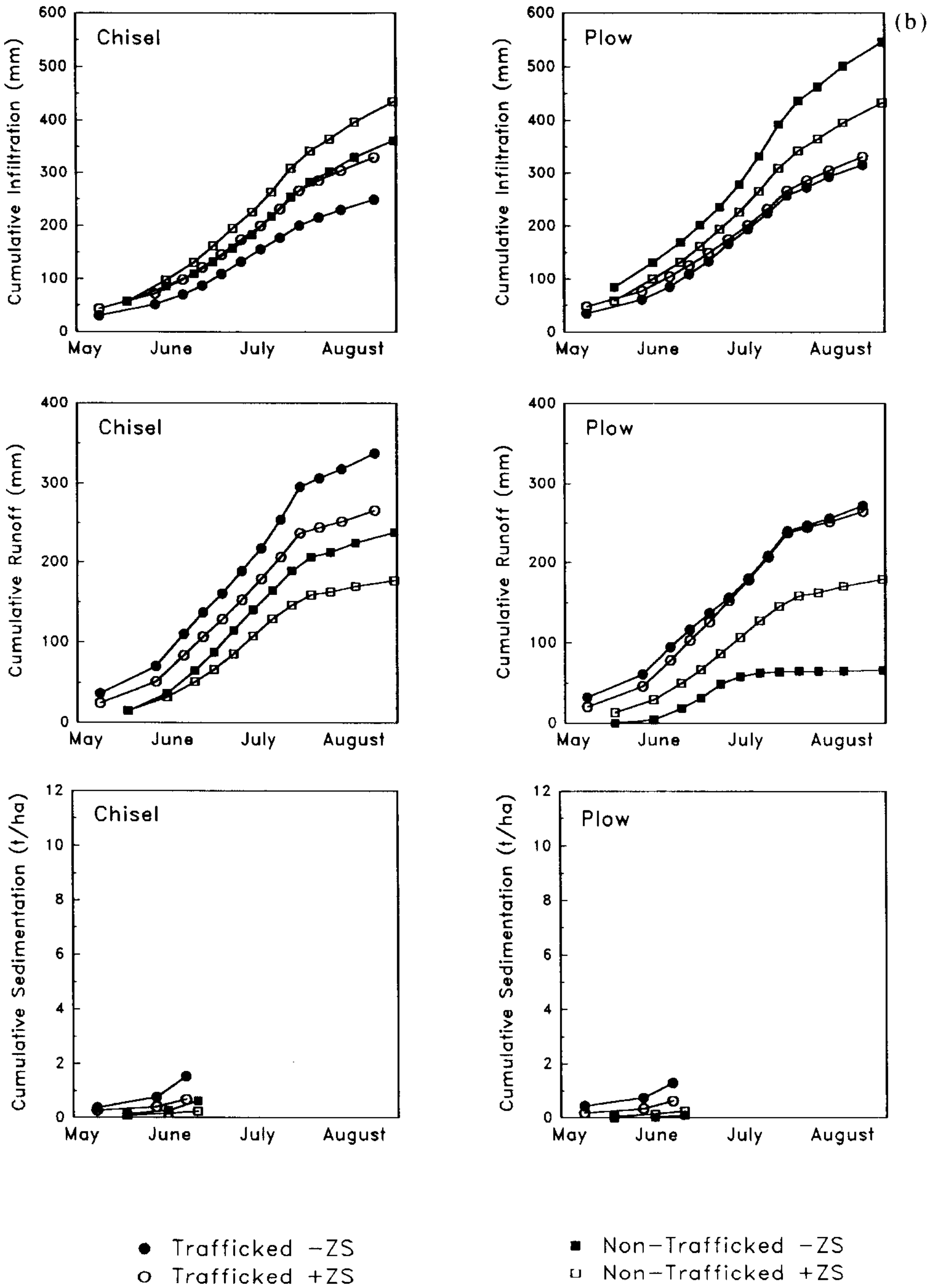


Fig. 1. Seasonal cumulative infiltration, runoff, and sedimentation patterns for 1989; (a) mean fall tillage and fall disk responses; (b) fall chisel and fall plow responses. Use or non-use of zone subsoiling is indicated by +ZS or −ZS, respectively.


(b)
Chisel
Plow
Cumulative Infiltration (mm)
Cumulative Runoff (mm)
Cumulative Sedimentation (t/ha)
May
June
July
August
● Trafficked −ZS
○ Trafficked +ZS
■ Non−Trafficked −ZS
□ Non−Trafficked +ZS

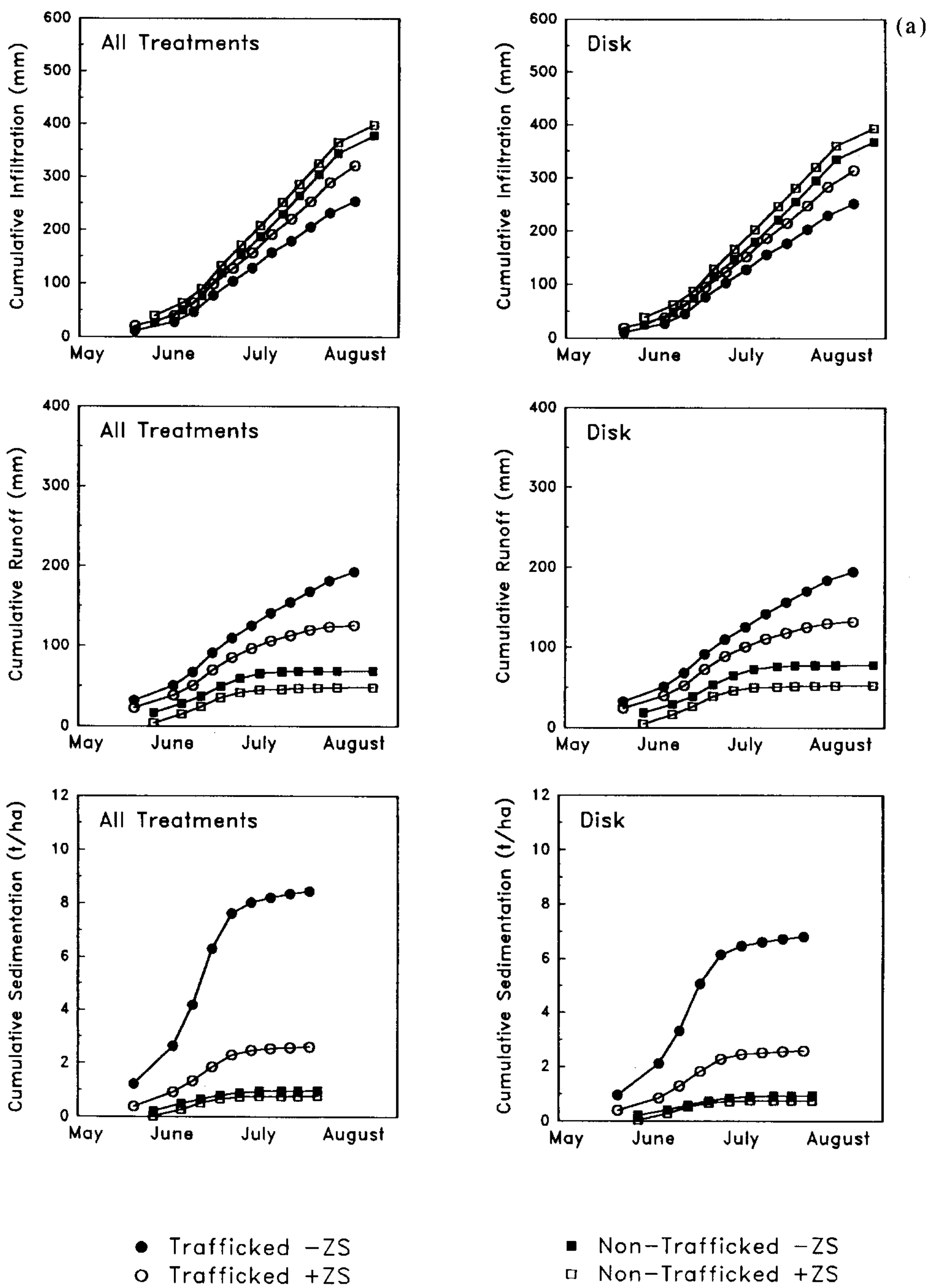
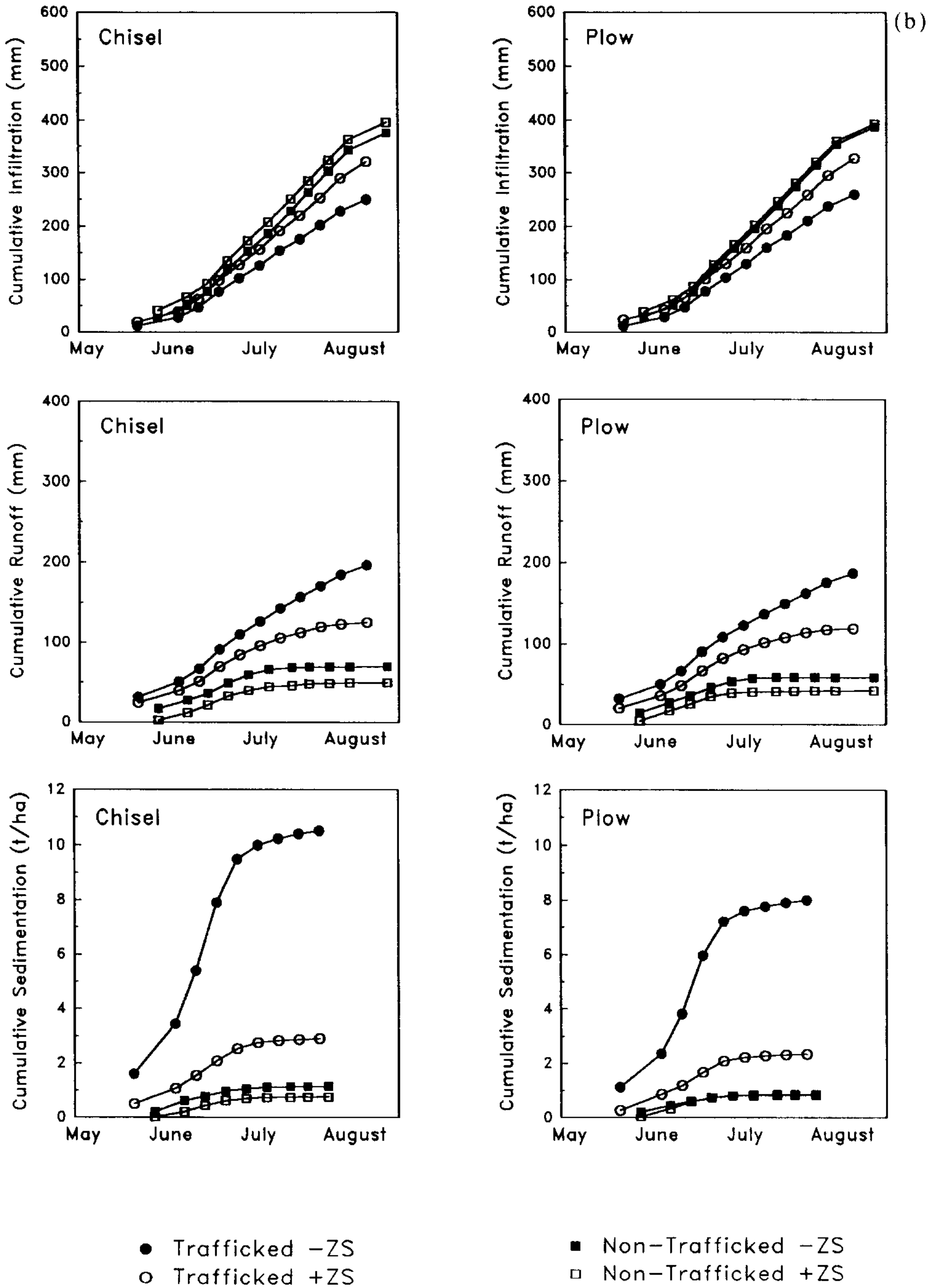


Fig. 2. Seasonal cumulative infiltration, runoff, and sedimentation patterns for 1990; (a) mean fall tillage and fall disk responses; (b) fall chisel and fall plow responses. Use or non-use of zone subsoiling is indicated by +ZS or −ZS, respectively.


(b)
Chisel
Plow
Cumulative Infiltration (mm)
600
500
400
300
200
100
0
May
June
July
August
Cumulative Runoff (mm)
400
300
200
100
0
Cumulative Sedimentation (t/ha)
12
10
8
6
4
2
0
● Trafficked −ZS
○ Trafficked +ZS
■ Non−Trafficked −ZS
□ Non−Trafficked +ZS

to fourfold greater without subsoiling. While runoff of zone-subsoiled traffic furrows became minimal by late July, runoff on non-subsoiled traffic furrows continued at a high rate until the last irrigation (Figs. 2(a) and 2(b)). This response was unlike that of 1989 in which runoff of subsoiled and non-subsoiled traffic furrows produced nearly identical or parallel curves.

Differences in the erosion rate became nearly non-existent by July 1990 (Fig. 2(a) and 2(b); slopes of cumulative sediment loss curves became parallel). July corresponds to complete canopy coverage and vine intrusion into furrows. Although infiltration and runoff largely dictated the direction of change in erosion from the various tillage treatments, it is apparently not the only factor. This can be seen by comparing the ratio of sediment loss to infiltration (cumulative only to the termination of sediment monitoring) for the tillage treatments over the 2 years of the study (Table 3). Although infiltration (and conversely runoff) varied by as much as 20% among tillage treatments, the ratio of sediment loss to water infiltrated varied several-fold among treatments. The sediment:infiltration ratio was particularly reduced by zone subsoiling in 1990. If the runoff volume per se caused the differences in erosion among tillage treatments, these ratios should be nearly constant.

The ranking of erosion was not entirely consistent between years. Generally, zone subsoiling substantially reduced erosion, especially in the more erosive traffic furrows. Also, fall chiseling had more erosion than fall plowing or fall disking, except with the addition of zone subsoiling. A major mechanism associated with the increase of infiltration and reduction of erosion in the zone-subsoiled treatments was the slowing of stream advance. While this increased infiltration and reduced erosion, it could pose its own management problems. A slower advance rate implies a greater difference in infiltration between the top and bottom of a furrow-irrigated field. This implies a greater variation in the field away from optimal soil water storage and availability for the crop, and can cause a loss of mobile nutrients from the rooting zone into the groundwater when excessive infiltration occurs. In this study, the negative factors stemming from such an increase in soil water variation were more than offset by other positive crop responses. Zone subsoiling with fur-

TABLE 4

Effect of fall tillage and spring zone subsoiling on shoot dry weight sampled 5 June 1990

Zone subsoiling	Disk	Chisel	Plow	Mean
Yes	1.74	2.06	1.97	1.92[a]
No	1.23	1.23	1.52	1.33[b]
Mean	1.49[a]	1.65[a]	1.74[a]	

Values with the same superscript for fall tillage or zone subsoiling do not differ at the 5% probability level, using Duncan's multiple range procedure.

TABLE 5

Effect of fall tillage and spring zone subsoiling on final tuber yield and grade. Use or no use of zone subsoiling is indicated by +ZS or −ZS, respectively. The zone subsoiling fall tillage interaction term is indicated by ZS×FT

	Tuber characteristics					
	Yield ($t\ ha^{-1}$)	Grade 1 yield ($t\ ha^{-1}$)	% grade 1	% grade 1 >284 g	% grade 1 114–284 g	Spec. grav.
1989						
Zone subsoil	39.4	24.9	62.6	29.1	33.5	1.080
Non Subsoil	36.3	21.1	57.2	27.0	30.2	1.079
Fall disk	37.8	22.8	59.4	30.0	29.4	1.078
Fall chisel	35.3	21.2	58.9	27.1	31.8	1.080
Fall plow	40.4	25.0	61.5	27.1	34.4	1.079
Disk +ZS	41.5	26.1	62.4	33.6	28.8	1.078
Chisel +ZS	35.4	22.2	62.2	26.7	35.5	1.081
Plow +ZS	41.2	26.3	63.1	26.9	36.2	1.080
Disk −ZS	34.2	19.4	56.4	26.3	30.0	1.078
Chisel −ZS	35.1	20.1	55.5	27.5	28.1	1.079
Plow −ZS	39.6	23.8	59.8	27.3	32.6	1.079
Probability (%)						
Zone subsoil	NS	9.09	3.58	NS	2.29	NS
Fall tillage	7.59	8.34	NS	NS	NS	NS
ZS×FT	0.06	NS	NS	0.35	NS	NS
1990						
Zone subsoil	41.9	26.9	64.2	14.9	49.3	1.083
Non-subsoil	37.7	21.3	56.5	12.9	43.6	1.083
Fall disk	38.1	23.5	61.3	13.3	48.0	1.082
Fall chisel	40.9	24.5	59.4	15.2	44.1	1.084
Fall plow	40.4	24.4	60.3	13.0	47.3	1.083
Disk +ZS	41.6	26.8	64.1	14.4	49.7	1.082
Chisel +ZS	42.2	26.9	63.7	16.0	47.7	1.084
Plow +ZS	41.8	27.2	64.8	14.2	50.6	1.083
Disk −ZS	34.6	20.2	58.5	12.2	46.3	1.083
Chisel −ZS	39.6	22.1	55.1	14.5	40.6	1.084
Plow −ZS	39.0	21.6	55.8	11.9	43.9	1.083
Probability (%)						
Zone subsoil	0.08	0.36	5.94	NS	6.03	NS
Fall tillage	NS	NS	NS	NS	NS	NS
ZS×FT	6.14	NS	NS	NS	NS	NS

NS, not significant.

row irrigation would require greater attention by the irrigator to deliver water uniformly across the field.

Crop responses

Fall tillage or zone subsoiling had no effect on the number of shoots per hill, which ranged from one to six with a mean of 2.82 and a standard deviation of 0.98. Shoot dry weight was unaffected by fall tillage (Table 4), but the zone-subsoiled treatment mean was 145% of non-subsoiled plots ($P<0.025$). Zone-subsoiled shoot dry weights were 141%, 167%, and 130% of non-subsoiled shoots for disk, chisel, and plow fall tillages, respectively. There was no significant fall tillage × zone subsoiling interaction. Soil temperatures in zone-subsoiled hills at depths of 5 and 15 cm were about 0.5°C higher (data not shown) than in non-subsoiled hills. This, coupled with lower bulk densities and more friable conditions in the zone-subsoiled hills, probably promoted earlier sprouting and emergence.

There was a tendency for tuber weights in the fall-plowed plots to be larger in the mid-season plant samples (data not shown). Zone subsoiling significantly increased tuber yields in three of four mid-season samplings over the 2 years. Neither the mean number of tubers per hill nor root weights recovered were affected by any tillage treatment. However, the sampling procedure did not provide a good estimate of total root weight.

In 1989, total tuber yield, the percentage of grade 1 tubers greater than 284 g (10 oz), and tuber specific gravity did not differ ($P<0.10$), although all three showed favorable trends with zone subsoiling (Table 5). Zone subsoiling increased the yield of grade 1 tubers by 3.8 t ha^{-1}, increased the total percentage of US grade 1 tubers, and the percentage of grade 1 tubers in the 114–284 g (4–10 oz) size range. These results were similar to those from other tests in Idaho (Sojka et al., 1991). Plowing gave the largest total yield and yield of grade 1 tubers. Total yield and yield of grade 1 tubers more than 284 g had an interactive response between choice of fall tillage and zone subsoiling. Zone subsoiling significantly increased these yield/grade parameters after fall disking but not after chiseling or plowing. This interactive yield/grade response may relate to effects of traffic pattern on infiltration.

In 1990, zone subsoiling significantly improved all yield and grade parameters observed except the percentage of grade 1 tubers over 284 g and specific gravity, although the trend was for the percentage of grade 1 tubers over 284 g to increase. The choice of fall tillage produced no significant effect on any of the yield/grade parameters observed. The only interaction between choice of fall tillage and zone subsoiling occurred for total yield. No yield differences were found among fall tillages when zone subsoiling was also carried out. Yields were significantly lower, however, for fall-disked plots without zone subsoiling. The difference in the interactive tillage effects of infiltration on yield from year to year probably relates to spring field conditions and traffic patterns each year, as explained previously.

CONCLUSIONS

Zone subsoiling offers the potential to improve the quality of 'Russet Burbank' potatoes, and possibly also to improve overall yield, while simultaneously increasing infiltration and reducing erosion. These parameters were most improved by zone subsoiling when irrigating traffic furrows, which usually have less efficient intake properties, causing greater runoff and erosion. Although the changes in erosion were certainly related to runoff, they were also affected by other unidentified mechanisms associated with the zone tillage technique. This is evident from the lower sediment:infiltration ratios after zone subsoiling, which would have been identical if runoff alone was responsible for the erosion differences. Zone subsoiling would require some adjustment by the irrigators to optimize the system on their own farms. The potential benefits warrant consideration of this practice where poor production quality is associated with high rates of erosion or infiltration problems.

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